Spin Transport and Dynamics in Nanoscale Hybrid Structures

DMR **-** 0334231

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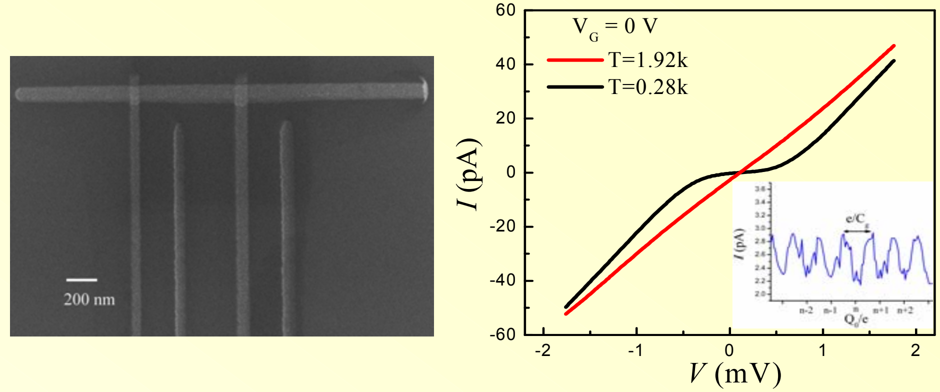
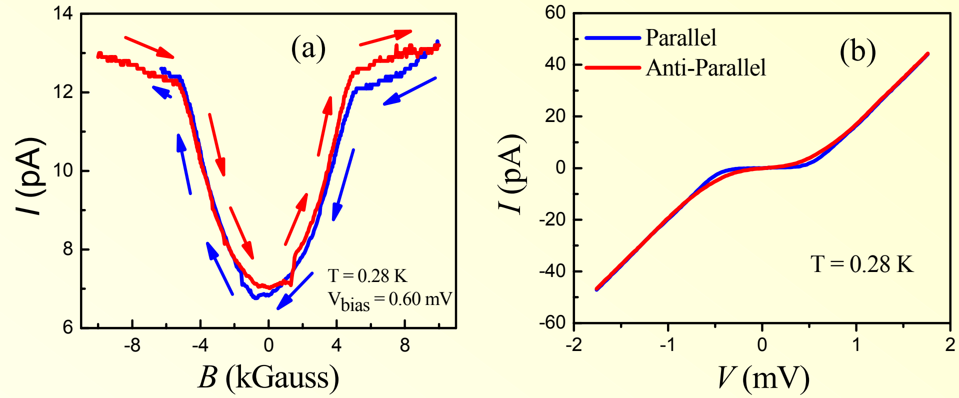
The objective of this project is to fabricate and characterize nanoscale hybrid junction structures that will reveal new physical aspects of quantum states and dynamic behavior of electron spins. Several interesting effects have been predicted for spin-dependent transport in ferromagnetic single electron transistors (FMSET), such as enhanced magnetoconductance in the Coulomb blockade region, superconducting gap suppression due to spin accumulation. Our goal is to experimentally verify these theoretical predictions and develop versatile spin electronic devices using single-electron spin as a binary variable, which so far has been pursued based on the behavior of large numbers of spin-polarized electrons.



Left: SEM image of a FMSET with Al as the island and Co as the FM electrodes. Right: *I-V* characteristics of the device, showing the gap at low temperature and current oscillation vs gate voltage (inset).



(a) Current vs. sweeping field; (b) *I-V* characteristic of the FMSET measured at parallel and anti-parallel states of the Co leads. The superconducting gap is suppressed at anti-parallel configuration.

For decades, electronic devices have been relying on the transport of the charge of electrons. Another property of electron - spin, has been often ignored. The electrons have two spin directions, spin up and spin down. In normal materials, the number of spin-up electron equals to the number of spin-down electrons. But in a ferromagnetic material, these two numbers will be different when the material is magnetized. The spin direction which has more electrons is called majority spin and the other is called minority spin. When two ferromagnetic materials in contact have the same majority spin direction, the electrons can easily flow from one material to another, facing relative low resistance. If the two materials have different majority spin direction, *i.e.* in one material, the up spin is majority spin, and in the other material, the down spin is majority spin, then electrons face higher resistance when flowing from one material to the other compared to the previous case. In our experiment, we fabricate a single electron transistor with a thin metal film - Al (which becomes superconductor at temperature below 1.4 K) as island, and ferromagnetic material as two leads. In between the leads and the island, there is a thin insulating layer, forming the tunnel junctions. There is also a gate electrode capacitively coupled to the island, tuning the island electron density. For such a device with ultrasmall junctions (70 nm x 70 nm), the electron moves one by one when two criteria are satisfied: (1) charging energy $e^2/2C_\Sigma >> k_BT$ (thermal energy), where e is the electron charge, C_Σ is the total capacitance of the device. k_B is Boltzmann constant, and T is the temperature; (2) Tunneling resistance R_T is much higher than resistance quantum: $R_T >> h/e^2$, where h is Plank's constant. Condition (1) means that the energy required to add a charge onto the island must exceeds the available thermal energy to ignore the thermal fluctuations; and condition (2) ensures that the wave function of an excess charge electron on the island is localized so that quantum fluctuations of the electric charge are negligible. Since the current through the device is a function of both the bias voltage across the leads and also the gate voltage, this device has the name "single electron transistor". Now, when the leads are magnetized, spin-polarized current from one ferromagnetic lead causes a non-equilibrium effect of spin accumulation in the non-magnetic Al island. This injected spin can be detected by the other ferromagnetic lead. Our measurements are carried out at low temperature T=0.28 K. At this temperature, Al becomes a superconductor. The single electron tunneling effect is shown in the measurement, and we have observed that the accumulated spin on the Al island suppresses its superconducting gap. This research provides a method to control single electron spin, and explores the ways to develop spin based nanoscale electronic devices.

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Education:

In this NIRT team, there are a total of eight graduate students trained in the program and have presented papers at conferences. Five postdocs (partially funded from this program) have been involved. Six undergraduates have participated in the research. Two of the undergraduates have gone on to graduate study in materials physics having won the NSF National Graduate Fellowship. There is also one high school student involved in this project, who is going to attend CalTech in the Fall as a freshman..

Societal Impact:

The ability to manipulate electron spin states is critical to extremely high-density information storage, electron-spin-based quantum computing, magneto-electronic sensors, and perhaps future spin electronic devices and systems yet to be imagined. As the trend of device miniaturization continues, such applications require deep understanding of the fundamental physics of spin dependent transport in nanoscale structures. This work contributes to current research in spintronics community and provides more comprehensive understanding of the spin dynamics to develop innovative spin based nanoelectronic devices.